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A MODEL OF THE HUMAN SUPERVISOR.

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0. *Summary.*

The outline of a possible construction of a general model of the human supervisor's behavior is given. In the description of the model very much attention is paid to its basic philosophy and the underlying thoughts and concepts - the system theoretic evaluation is only briefly considered at the end, where some results are given of an application of the model. Based on the notion of the state of the supervised system, which contains all information needed for the examination of all system functions as well as the deduction of adequate correction signals, three basic submechanisms are accepted to constitute the model - the observer/reconstructor part, the decision-making part, and the controller part. For the relations between the task variables (system dynamics, noise parameters, supervisory task) and the parameters of the different submechanisms of the model a set of hypotheses is postulated. Then the verification of the model hypotheses is considered using variations in the task variables. For that purpose the three basic submechanisms are given in terms of the operational structures. For the observer/reconstructor part an optimal observer is introduced, for the decision-making part the description is given in terms of decision rules, and the controller part is developed along the line of a minimum-time criterion.
Finally, for the identification of the model parameters an approach is suggested which makes use of a multi-dimensional error criterion. Each of the elements of this multi-dimensional criterion corresponds to a certain aspect of the supervisor's behavior, and is directly related to a particular part of the model and its parameters. This approach offers good possibilities for an efficient parameter adjustment procedure.

1. *Introduction.*

The ever-increasing automation in industry has put the human operator more and more in a new role relative to the machine - the role of a supervisor over an automatically controlled system. This means that at the occurence of deviations, failures and disturbances in the operation of the system the human supervisor has to perform a task of corrective actions, i.e. he has to detect the errors and to decide if corrections are necessary. Therefore, the supervisory task involves monitoring and observation as well as decision-making and control.

For the design of adequate man-machine interfaces a good knowledge and understanding of the supervisor's behavior is necessary. Descriptive and normative models of the supervisor can add significantly to the still missing know-how. However, to be useful in design of automated systems of diverging complexity and character, the new models should be valid over a broad range. This calls for models based on a general framework, which can be applied to a variety of situations. Empirical models, developed for a particular set-up, are of no interest.

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In this paper we give an outline of a possible construction of a general model of the human supervisor's behavior. We are very aware of the fact that our attempt is just a first step towards the final goal of a useful tool in the design of man-machine systems, for instance with respect to the limited number of aspects of the supervisory task which is taken into account. In the description of the model we pay very much attention to its basic philosophy and the underlying thoughts and concepts, leaving the system theoretic evaluation to the last section where we give some results. The reason for this approach lies in our wish narrow the gap between experimental psychology and system engineering modelling, which, in our view, would be very desirable.

2. *Evaluation of a supervisory model.*

The human supervisory task can be considered as a control task, but on a higher hierarchical level, due to the fact that the direct control of the system is accomplished by the automatic controller. Therefore, a control model can serve as a starting point in the evaluation of a supervisory model. For this purpose, in our view, the optimal control model (Baron, Kleinman, Levison [1]) is the best choice, because of the following reasons:

- composed of some basic submechanisms it is a normative model which on the one side allows the system theoretical effectuation, and on the other side presents possibilities for interpretation of the parameters from psychological and behavioral sciences point of view.
- essentially this model is capable of handling very complex situations as encountered in supervisory control tasks.

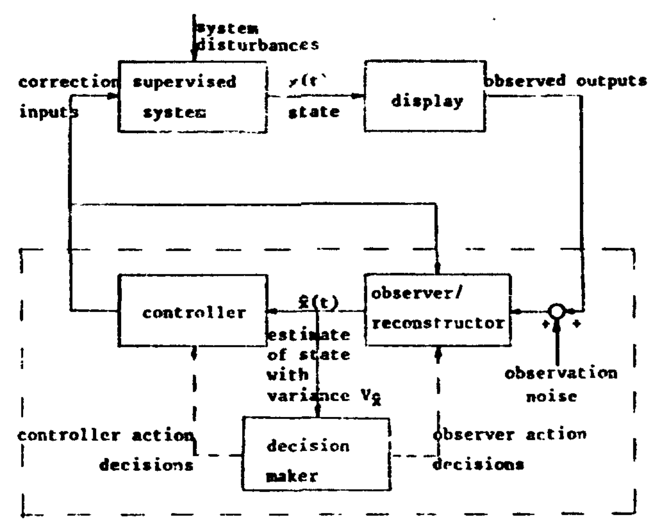

Figure 1. Basic concepts of the supervisory model.

As in the optimal control model the basic underlying thought of the model of the human supervisor given here is the separation of the model in a observer/reconstructor part and a controller/decision making part. This separation is based on the concept of the state of the supervised system, for the state contains *all* the information needed for the examination of all system functions as well as the deduction of adequate correction signals. Since the system state itself is not directly available, from all the information at the supervisor's disposal, i.e. the observed system outputs and the correction inputs, and the knowledge of the system dynamics (the internal model of the supervisor), at the best an estimate or reconstruction of the state can be obtained: this estimate is generated by the observer/reconstructor part of the model. The estimate of the system state obtained this way and the statistical uncertainties related to this estimate are the sources of information upon which the controller/decision-making part of the model can come to corrections and intervening actions. The control strategy and the decision rules relevant to these corrections and actions follow from the system dynamics and the supervisory task to be performed by the operator. The basic concepts of the supervisory model, i.e. the separation in three submechanisms, is given in Fig 1.

In the following sections we will discuss the assumptions and the hypotheses upon which the evaluation of each of the submechanisms can be based. For reading convenience, however, we first give some definitions of terms and quantities involved in the modelling process.

3. *Definition of terms.*

Supervised system: the system to be controlled and monitored, or, in general, to be supervised. This includes the process as well as the automatic controller.

System disturbances: noisy inputs to the supervised system which cannot be controlled by the supervisor.

State x(t) of the supervised system: collection of (physical) quantities in the system which, expressed in a momentary value, contain all information on the affectuation of the system inputs in the past.

Display: system which provides the representation of the state x(t) of the supervised system to the supervisor; usually, a reduction of the explicit information content of x(t) takes place here.

Observed outputs: the signals giving information about the state of the supervised system which are available to the supervisor, and which are obtained by observation of the display.

Observation noise: noisy signal which represents the supervisor's uncertainty about the observed outputs.

Observer/reconstructor part of the model: (dynamic) system which generates a reconstruction of the state of the supervised system from the information received from the observed outputs and the correction inputs. Due to the uncertainties in the available information (as a result of the observation noise and the unknown system disturbances), and the reduction of the information by the display, this reconstruction cannot be better than an estimate with a certain error.

Estimate $\hat{x}(t)$ of the state: reconstruction of the state of the supervised system, which takes into account the statistical properties of the uncertainties in the available information. The estimation error is characterized by the estimation variance $V_{\hat{x}}$.

Controller part of the model: a system that generates a correction signal for the supervised system from the obtained estimate of its state (usually in the form of set points for the automatic controller).

Decision making part of the model: a system that, based on the estimate of the state of the supervised system and its error variance, comes to decisions about the realisation of control actions (the adjustment of set points) and the observation actions (the sampling of a controlled variable, for instance).

Correction inputs: the signals generated by the supervisor to make corrections to the controlled variables of the supervised system.

4. *Model hypotheses.*

For the relations between the task variables (sytem dynamics, noise parameters, supervisory task) on the one hand and the parameters of the different submechanisms of the model on the other hand, the following hypotheses are essential:

- The observer/reconstructor part of the model is assumed to be independent of the supervisory task to be performed by the supervisor, and thus only depends on the supervised system (to which system do the observed outputs belong, and, therefore, which interrelation between them does exist?), the display (in which way are the state variables represented in the observed outputs?) and the noise parameters (what are the characteristics of the uncertainties in the observed outputs?). Along system theoretical lines the concept of the observer/reconstructor part can be affectuated for a given set of system parameters and noise parameters. The result shows the reflection of the supervised system and the display within the observer/reconstructor part of the model. This fact offers the opportunity to the introduction of an internal model concept to model the supervisor's knowledge of the system dynamics. Assuming a complete notion of the dynamics of the system by the supervisor, the statistical properties of the observation noise are the parameters of the observer/reconstructor part of the model.
- The controller part of the model is assumed to be independent of the observation/reconstruction process, and thus only depends on the supervised system (which system will receive the correction signals, so in what way will these signals influence the state of the system) and the supervisory task (what are the controlled variables, and which control effort is allowed for the necessary corrections?). Also for this control problem the solution is provided by system theoretical elaboration, which offers several possibilities to model the supervisory task (for example, is the supervisory task given in terms of a quadratic performance index, or in terms of a minimum time criterion?). Once more, the internal model concept can be introduced to model the subjective interpretation of the human supervisor of the supervisory task laid upon him. This is an extension of the internal model concept mentioned before. The weighting factors in the supervisory task are the parameters of the controller part of the model.

- The decision-making part of the model is assumed to operate on the controller part as well as the observer/reconstructor part of the model. This is because of the fact that the human supervisor must make decisions to come to corrective control actions, but also should watch the observation process and, if necessary, take action to avoid inadmissable uncertainties in the estimates of the state of the supervised system (this kind of decisions arises, for instance, when the supervisor has the opportunity to sample from time to time the controlled variables more accurately than can be deduced from direct observation of the continuously available outputs). Therefore, the total decision-making process can be separated into two different groups of decisions, viz. the decisions related to control actions and the decision related to observation actions. A general concept which can be used as the basis of the decision-making part of the model, and which postulates the relation between task variables (the system dynamics, the display, the supervisory task, the noise parameters) and the decisions or the decision rules, is not available yet. To be able to develop such a concept in the future, the model of the decision making part will be based, temporarily, on a set of free parameters, given in terms of decision rules and the crossing of certain threshold values. After determination of these free parameters, i.e. the threshold values, in different experimental situations, a concept could be developed for the modelling of a relation between the threshold values and the independent task variables. With regard to the decisions concerning control actions, the threshold values are related to the correction signals (a control action will take place if the necessary correction exceeds the particular threshold value), and for the decisions concerning observation actions the threshold values are related to the uncertainties of the estimates of controlled variables which can be sampled (a sample will be taken if the uncertainty of the estimate of the controlled variable exceeds the particular threshold value). It should be noticed that the information needed for these decisions in terms of the correction signals and the uncertainties of the estimates can be directly derived from the estimate $\hat{x}(t)$ of the state and the error variance $V_{\tilde{x}}$, making use of the control algorithm and the parameters of the display, respectively. The threshold values in the decision rules are the parameters of the decision making part of the model. In fact, these parameters are *not* independent quantities, but are related to the supervisory task, the noise parameters, and the dynamics of the supervised system and the display. This relation will be considered as a topic for future research.

The outline of the modelling concept introduced above has a very general character. The model gives a qualitative as well as a quantitative description of the human supervisory behavior, making it interesting from psychological and system theoretical point of view. The system theory provides the necessary evaluation of the submechanisms of the model, while the parameters involved are problem related quantities which have a direct meaning and practical significance (human uncertainties in the observation process, the supervisory task, the system dynamics, the thresholds of the decision rules).

The fundamental separation between the observer/reconstructor part and the controller/decision-making part of the model is an attractive feature of the postulated model, which allows the experimentator to choose the variation of task variables appropriately, and so study each of the resulting effects individually. The verification of the model hypotheses will be considered in the following section.

It should be noticed that in the description of the model given above it was assumed that the model will be applied to supervisory control situations where the time constants of the system exceed values of 10 seconds and more, and thus that the human control capacities are not severely limited by his inherent reaction time or his muscular system (in the applications of human control of fast response systems modelled by an equivalent delay time).

A final remark concerns the modelling of the human uncertainties in the perception of the correction signals. Here two different conceptual solutions could be suggested. According to the first concept, which is commonly accepted as, for example, in the optimal control model (Baron, Kleinman, Levison [1]), these uncertainties can be modelled by a motor noise which is additive to the correction (control) signal; this approach was shown to be successful in the case of modelling the human control behavior, where this noise in fact represents the uncertainties of the operator's control movements. The second concept, however, might be more appropriate for the supervisory control situation. Rather than by a motor noise, the human perceptual uncertainties are now modelled by an additional observation noise, which acts on the feedback signal to the observer/reconstructor part of the model only. Which one of these approaches gives the best description of the human supervisory behavior can be determined by direct application of the two concepts on practical data, which will be part of the investigation.

5. *Verification of the model hypotheses.*

Explicit verification of each of the model hypotheses is very difficult, if not impossible, due to the strong interaction of the model submechanisms. What can be done, however, is the verification of the influences on the model of each of the task variables, which implicitely verifies the total set of hypotheses. The following variations of task variables are to be considered:

- *Variation of the intensity of the system disturbances.*
  Variations of the intensity of the system disturbances will conceptually influence the observer/reconstructor part of the model, but not the controller part. Assuming an optimal full-order observer as the observer/reconstructor part of the model, the relation between the system noise intensity matrix and the observer gain matrix as well as the error covariance matrix is completely prescribed by the system theoretic solution of the stochastic optimal reconstruction problem. An increase of the system noise intensity, relative to the other noise sources in the closed loop, will also result in an increase of the observer gain matrix, which reflects the fact that more attention should be paid to the observed outputs (increasing the speed of the state reconstruction). Also, an increase of the resulting error variance matrix, which corresponds to an increase of the estimation uncertainty, should coincide with an increase of the repetition rate of the observation actions of the decision-making part of the model. However, the submechanisms of the controller part and the decision-making part of the model should be invariant under the variations of the intensity of the system disturbances.

- *Variation of the display.*
The display is reflected in the observer/reconstructor part of the model, so variation of the display parameters should be effective here. As far as the variations affect the observability of the supervised system (which information is available in the observed outputs for the reconstruction of the state), the resulting error variance will be affected too. Again, such variations and the resulting error variance and observer gain matrix are prescribed by the system theoretical solution of the stochastic optimal reconstruction problem, and can be verified accordingly. Additional to these consequences of variations of the display parameters also a drift in the observation noise characteristics may be expected, which might change the whole picture. This must be examined very carefully. The submechanisms of the controller part and the decision-making part of the model should remain the same for various displays, however.
- *Variation of the supervisory task.*
Variations of the supervisory task are conceptually of no influence on the observer/reconstructor part of the model, but are only of importance to the controller part of the model and probably also to the decision-making part (i.e. the threshold values). The supervisory task can be varied, for instance, by changing the admissable control effort by proper instruction of the supervisor. Depending on the assumed structure of the supervisory task, such as a quadratic performance index or a minimum time criterion with limited signal magnitudes, either a relative weighting of control effort against result will take place, or an actual limitation of the admissible corrections. The choice for the modelling of the supervisory task also determines the nature of the resulting correction signal. In case of a quadratic performance index the model will generate a continuous correction signal, whereas in case of a minimum time criterion a discrete signal will result (bang-bang character, e.g. Crossley and Porter [2]). Noting the fact that in supervisory control situations the human supervisor generates signals that are rather discrete than analogue, it is very likely that a model based on the minimum time criterion will give better results as far as the input-output description concerns of the supervisor's behavior. This expectation was confirmed by application of such a model on practical data (Hupkes [3], Beliën [4]). As the parameters in the minimum time criterion, the magnitude of the admissable corrections can be considered or the length of the time interval during which a perceived deviation of the controlled variable must be corrected by a constant input to the system. The relation between these parameters is determined by the dynamics of the supervised system.
For the relation between the supervisory task and the threshold values of the decision-making part of the model, no modelling concept has been postulated yet. In our investigation we follow the approach of determining first the values of the parameters of the minimum time criterion and the threshold values for different supervisory control situations, which give an optimal description of the human input-output relation. After that, we intend to analyse the results and come up with a modelling concept which will fit the data, and which gives the threshold values in terms of the supervisory task and the dynamics of the supervised system.
- *Variation of the dynamics of the supervised system.*
The dynamics of the supervised system are involved in all mechanisms of the model, thus in the observer/reconstructor part as well as the controller and decision-making part of the model. As far as the influences on the observer/reconstructor part and on the controller part are concerned the postulated modelling concepts can be evaluated and verified by variation of the dynamics of the supervised system. For the influences on the decision-making part this working scheme must be modified, since there was no causal relation postulated between the system dynamics and the threshold values. Here, a similar procedure must be followed as was suggested for the investigation of the relation between the threshold values and the supervisory task. And again, the final objective will be to develop a modelling concept which gives the link between these parameters.
Careful attention should be paid to the influence of the dynamics of the supervised system on the observer/reconstructor. The structure of this part of the model is such that it includes a reflection of the supervised system and the display, which can be considered as the internal model of the supervisor. It is not very likely that, regardless of the complexity of the supervised system, the internal model can be assumed to be an exact copy of this system and the display. This question will be subject to close examination by varying the order of the supervised system and matching full-order observers as well as reduced order observers in the observer/reconstructor part of the model. Also lower order simplified models could be substituted, giving the opportunity to compare the description of the supervisor's input-output behavior obtained in this way with other models. So far, we have no experience with these techniques yet, due to the fact that our experimental set-up involves a low order supervised system which is too simple to raise this problem.

6. *Identification of the model parameters.*

Before attention can be paid to the verification of the model hypotheses, the crucial problem must be considered of how to compare the model behavior with the behavior of the supervisor. The most important quantitative measure for the comparison is given by the resulting correction signals generated by the model and the human supervisor. The most common technique makes use of a criterion which is defined on the error of the two signals, usually in the form of the time average of the squared error. The parameters of the models are then adjusted such that this criterion has a minimum value. This method is quite satisfactory in most cases if continuous signals are considered. In our case, however, we are dealing with signals which are rather discrete varying in time than continuous. Application of the quadratic error criterion on these discrete signals, where only the amplitude of the signal is taken into account, leads to bad results (Hupkes[3], Beliën[4]). To achieve a realistic mutual resemblance of the discrete signals it turned out to be very essential to define the error criterion not on the amplitude only, but also on the time instants of changes in the amplitude of the correction signal.
A similar problem arises in the comparison of the other quantitative output of the model and the human supervisor, viz. the series of observation actions. Here only the time instants are of concern, and the amplitudes are of no importance.

As a result of the considerations given above, we would like to suggest an approach to the problem of comparison of the model and the human supervisor, which is based on the following criterion elements:
- the instants in time where the observer actions are taken (related to the relevant submechanism of the decision-making part of the model),
- the instants in time where controller actions are taken (also related to the decision-making part of the model, but now to the other submechanism),
- the amplitudes of the correction signals (related to the controller part of the model).

This approach has the advantage of a direct coupling of the relevant parts of the model with each of the elements of the criterion. Also, along this line, the individual consideration becomes possible of the different aspects of the resemblance of the supervisor and the model. A consequence of the distinction between the different aspects is the introduction of a vector valued criterion function (e.g. Steward, Kavanaugh, Brocker [5]), which complicates the parameter optimization procedure. On the other hand, the isolation of these different aspects and the direct relation with the related parts of the model offers the possibility of a successive optimization of each of the parameters involved, which can be performed outside the loop. Assuming a given model of the observer/reconstructor part of the model, the threshold values of the decision-making part relevant to the observer actions can be adjusted to achieve a best fit of the measured series of instants. Then, having available the estimate of the state of the supervised system generated by the combination of the observer/reconstructor part of the model and the optimized series of observation actions, the procedure can be repeated with regard to the instants of controller actions and the other threshold values. Finally, the best fit of the amplitudes of the

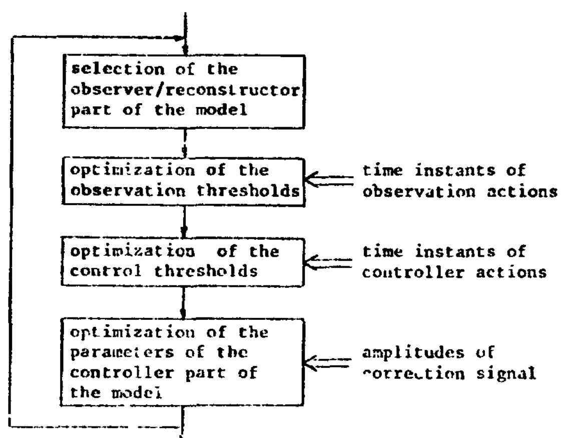

Figure 2. Off-line parameter adjustment in successive steps.

correction signals can be obtained by adjustment of the parameters in the controller part. If necessary, the procedure can be iterated for the adjustment of the parameters of the observer/reconstructor part of the model (see Fig. 2).

The successive parameter optimization procedure, as well as the combined optimization of the total set of parameters in the vector valued criterion function are now being tested. For the optimization of the vector valued criterion function we make use of a random search method (Steward, Kavanaugh, Brocker [5]), which avoids some complications as encountered in the application of gradient techniques, like termination of the procedure in local minima and the conceptual problem of the non-existence of the derivatives for some parameters.

7. *An application of the modelling concept.*

The model discussed before has been applied to a simple supervisory task in a semi-automatic control situation (see Fig. 3). For a given system, which is disturbed by noise, the quality output $y_1(t)$ must be supervised by the human operator. The momentary value of this quantity cannot be observed continuously by the supervisor, but on his request, will be sampled and become available to him. However, these samples are delayed in time due to processing analysis. The other system output $y_2(t)$ is the feedback signal for the automatic controller, and is also observed by the supervisor. The output $y_2(t)$ is related to the quality $y_1(t)$, but is more corrupted by noise. Using the available information, the supervisor must make proper adjustments to the set points of the automatic controller in order to maintain a good quality. Also, taking into consideration the costs of sampling, he must decide whether or not to ask for a new sample to obtain more accurate, but delayed, information.

In the experimental set-up a digital computer is used to simulate the system and to generate the signals. The subject sits behind a panel, where the information is displayed and the set points can be adjusted. To avoid boredom, two systems of the same character are to be supervised simultaneously by the subject. For this situation, which is commonly found in industry,

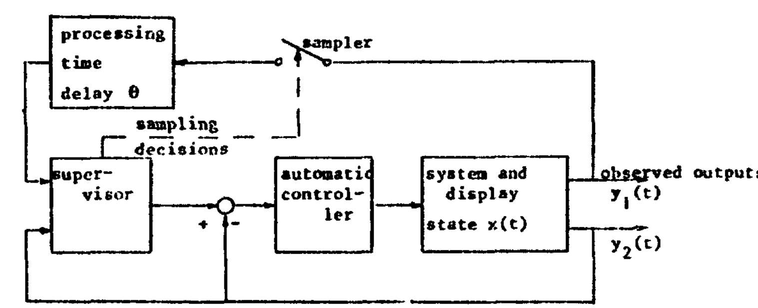

Figure 3. Experimental supervisory situation.

for instance in chemical plants, a model is postulated for the description of the supervisor's behavior, which is based on the concepts given before:

- Using the information about $y_2(t)$ and the last sample $y_1(t_k)$ the supervisor will make an estimate $\hat{x}(t)$ of the state $x(t)$ of the system. The variance of the estimation error of this estimate will be determined by the uncertainties in the observed quantities and by the time elapsed since the last sampling instant.
- Depending on the supervisory task to be performed, the value of the estimate of the state, and the uncertainty of this estimate, the supervisor will make two kinds of decisions:
  a) Decisions to ask for a new sample of the quality signal, taking into account the costs of sampling (observation action decision).
  b) Decisions to adjust a new set point for the automatic controller (controller action decision).
- If the supervisor has decided to correct the set point of the controller, he will select a new value using his information on the estimate $\hat{x}(t)$ of the state of the system.

The system theoretic evaluation of the different parts of the model will not be given in detail. We only give some general comments.

The observer/reconstructor part of the model consists of an optimal full-order observer (Kalman filter) acting on the continuously available output $y_2(t)$. The sampled observation $y_1(t_k)$, which becomes available at time $t_k+\theta$, where θ is the processing time delay, is assimilated in the filter by setting it back in time, process the additional (low noise) information resulting in a better estimate $\hat{x}(t_k)$, and, once again, use $y_2(t)$ in the interval $(t_k, t_k+\theta)$ to arrive at a better estimate $\hat{x}(t_k+\theta)$. Then, until a new sample becomes available, the filter continues its action using $y_2(t)$. The result is an optimal estimate $\hat{x}(t)$ of the state of the system, which is continuously available along with its error variance. From this estimate $\hat{x}(t)$ of the state also an estimate $\hat{y}_1(t)$ of the quality output, and its error variance, are derived using the system output equation.

The decision-making part of the model was designed according to the general outline given in section 4. This means that a decision rule was introduced based on the estimate $\hat{y}_1(t)$ and its error variance resulting in the decisions to ask for a new sample, and another decision rule based on the new set point value to make the necessary correction on the quality output resulting in the decisions to change the set points. The threshold values in the decision rules are the parameters of the decision-making part of the model.

For the controller part of the model we made use of a control strategy which is based on the correction of the perceived deviation of the quality output of the system by a new set point value which is held constant over a certain (minimum) period of time. The length of this time period is the parameter of the controller part of the model.

For the particular experimental set-up the dimension of the state $x(t)$ is three, the outputs $y_1(t)$ and $y_2(t)$ and the set point signal are one-dimensional, and the system disturbances are two-dimensional. So the model includes only three parameters (two threshold parameters in the decision-making part, and one interval length parameter in the controller part), for there are no parameters involved in the observer/reconstructor part, being almost completely determined by the given system parameters, the noise characteristics of the system disturbances, and the prescribed optimal observer algorithms. The only undetermined parameters of the observer/reconstructor part are the intensities of the observation noises in $y_1(t)$ and $y_2(t)$, the first of which is taken to be zero and the other is assigned a value proportional to the variance of the observed quantity itself ($0{,}01\pi V_{y2}$, according to the experimental data of Baron, Kleinman, Levison [1]). No motor noise has been included in the model, so no parameters are needed to characterize this noise.

The principle of the adjustment of the parameters to match the model outputs with the supervisor's outputs was described in section 6. A three dimensional vector valued criterion, defined on the set point values and the moments of decision to take observer actions and controller actions, was optimized using a random search method. Some results on the outputs of the model are given in Fig.4, which shows that a good fit of the supervisor's behavior can be achieved. Similar results couldn't be obtained using a one-dimensional optimization criterion for the parameter adjustment. Also, testing a model based on the acceptation of a quadratic performance index for the modelling of the supervisory task, the resulting set point variations showed such a complete different character that no good fit of the data could be obtained (Hupkes [3], Beliën [4]).

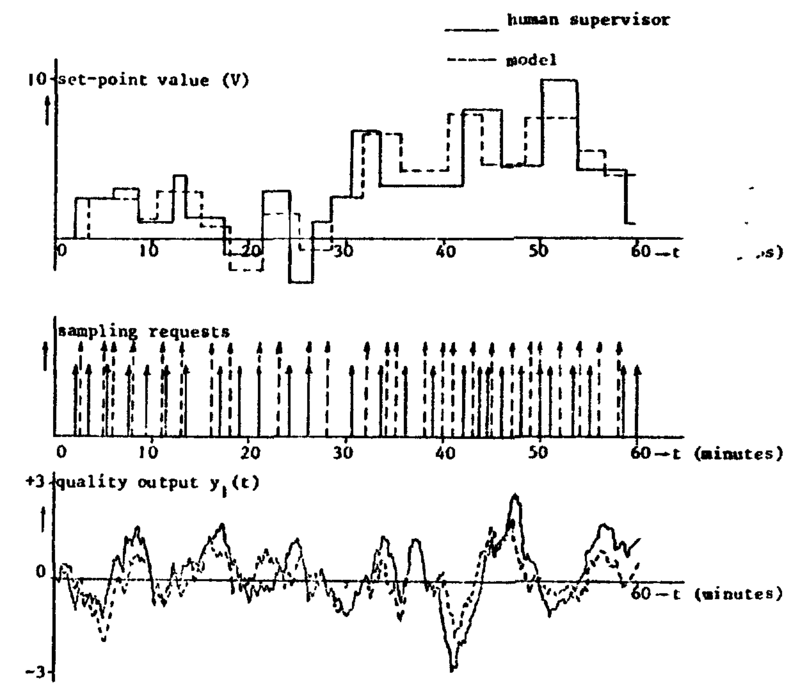

Figure 4. Outputs of the model and the human supervisor.

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